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Picosecond silicon metal-semiconductor-metal photodiode

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ABSTRACT

The ultrafast characteristics of crystalline-silicon metal-semiconductor-metal (MSM) photodiodes with finger widths and spacings down to 200 nm, subjected to femtosecond optical pulse excitations, was measured with a subpicosecond electro-optic sampling system. Electrical responses with full-width at half-maximum (FWHM) as short as 3.7 ps, at a corresponding 3 dB bandwidth of 110 GHz, were generated by violet-light excitation. These diodes are the fastest silicon photodetectors reported to date. Detailed bias and light-intensity dependence of the diode response has been measured. These results are used to obtain the velocity-field relation of electrons in silicon and to demonstrate the ideal transit-time-limited response of the diodes.

2. INTRODUCTION

In a recent publication,[1] we reported experimental results on the ultrafast response of silicon-based metal-semiconductor-metal photodiodes (MSM PD's). These diodes are attractive for integrated optoelectronic-electronic applications not just because of their speed, but also because of their compatibility in processing and lithographic requirements to the standard silicon integrated-circuit technology.

The MSM diodes were fabricated on crystalline silicon. The metallic fingers were in an interdigitated configuration with finger widths and spacings of 300 nm. Using a novel contact-free, zero-displacement electro-optic sampling technique,[2,3] we were able to measure the device response free of propagation distortion. The measured results showed that these diodes had response transient that contained a rapid, subpicosecond rise limited by the

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diode RC time constant, and a slower recovery limited by carrier transit to the electrodes. When red photons (around 800 nm wavelength) were used as excitation source, the transient full-width-at-half-maximum (FWHM) was 11 psec, and when violet photons (around 400 nm wavelength) were used, the FWHM was decreased to 5.5 psec. The much increased speed at violet was attributed to shallower photon penetration at this wavelength where the penetration depth is comparable to the diode finger spacing. By contrast, at red, the penetration depth is several micrometers and the excitation photons would create deep carriers that take longer time to reach the electrode.

Another important result in the time response of the MSM PD's was their recovery time after illumination, defined as the time for the diode to recover fully to the non-conductive state. This number is perhaps even more important than the simple FWHM parameter for consideration of practical applications, since it defines the maximum repetition rate that a stream of optical signals (such as that used in digital communication applications) can be resolved by the diode. We found that the recovery time was also much improved from red to violet, decreasing from more than 50 psec to less than 20 psec.[1]

Our experimental results at violet were in excellent agreement with one-dimensional Monte-Carlo calculations.[4] No attempts were made to simulate the results at red, which require two-dimensional computations.

In this correspondence, we report new results on the response of a 200-nm silicon MSM PD. Also, more detailed measurements of the dependence of the diode response on bias voltage and excitation light intensity will be presented to form a complete picture of the characteristics of these diodes.

3. EXPERIMENTAL RESULTS

The diodes reported here were fabricated and tested in a procedure similar to that reported in ref. 1. Electron-beam lithography and lift-off techniques were used to pattern the diode fingers on the Ti/Au metallization layer deposited on the surface of the semi-insulating silicon substrate. A typical diode under test was mounted as a shunt to a coplanar stripline (characteristic impedance $\approx 75\ \Omega$). The excitation source was a frequency-doubled femtosecond Ti:sapphire laser, and the probing source was at the fundamental frequency of the laser, guided in a total-internal-reflection mode through an electro-optic crystal tip.[2] The excitation and probing sources were focussed through the same set of objective lenses to allow zero-displacement sampling of the device response.[1] We will concentrate here on the results by violet excitations only, in order to avoid the more complex and problematic deep-carrier effects at longer wavelengths.

Figure 1 shows a comparison of the response of the 200-nm and 300-nm diodes to a 100-fsec laser source at red and at violet, with a 3V diode bias. The smaller diode had a transient FWHM of 3.7 psec, corresponding to a 3-dB bandwidth of 110 GHz, a performance previously achieved only in III-V compound diodes.[5] This result is again in close agreement with Monte-Carlo calculations that predicted a FWHM of 4 psec.[4] The 200-nm diode had a recovery time of about 15 psec.

When the diode bias was decreased, the response transient was slowed down, as shown in Fig. 2. This effect is attributed to the reduced electron velocity at lower electric field. It is well-known that electrons in silicon have a velocity-field relation that is linear up to an electric field about 3×10^3 V/cm, with velocity saturation occurring at about 5×10^4 V/cm.[6] (These numbers are for room-temperature, undoped silicon). Our measured speed of silicon MSM PD's can then be used to map this relation. Shown in Fig. 3 is a plot of the inverse pulse width (proportional to electron speed) versus the bias voltage. It is seen that velocity saturation occurs at a bias between 1.0 to 1.5 V. If we assume that all of the bias is applied to the carrier-depletion region between the MSM electrodes, this would correspond to a saturation field of 5 to 7×10^4 V/cm.

At all bias voltages, our results indicated that carriers generated by photons were completely swept into the electrodes. We have calculated the electron charge collected by the electrode by integrating the transient pulse, as shown in Fig. 4 (upper curve). It is seen that, although the pulse width is broadened when the bias is lowered (lower curve in Fig. 4), the integrated pulse charge remains constant. This is consistent with the concept that the diodes operate in a transit-time-limited mode,[4] with undiscernible carrier recombination and regeneration.

As the intensity of the excitation source was varied, the diode was found to respond linearly. Figure 5 shows the change in pulse height and in pulse integral when the light intensity was changed by a factor of 10. From the bias and intensity dependence, the quantum efficiency of the diode is calculated to be about 12 %.

4. CONCLUSION

Results presented here and in our previous publications[1,4,5] show that the silicon MSM diodes have characteristics well understood theoretically and thoroughly verified by experiments. We have previously used variable-wavelength laser excitations to pinpoint the speed limit of these diodes as due to the deep carriers generated by photons; in this report, we further demonstrate an ideal, transit-time-limited voltage and light-intensity dependence of

the diode transient response. Devices free of deep-carrier effect, as proposed by us,[1] are currently being tested. Their implementation into an integrated silicon detector circuit is also under way.

5. ACKNOWLEDGEMENT

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